Appendix A
The ALS as a Source of Intermediate-Energy X Rays

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1. Introduction

The Advanced Light Source (ALS) was optimized to produce extremely high flux and brightness in the vacuum-ultraviolet (VUV) and soft x-ray regions using undulator sources. It is also, however, an excellent source of intermediate-energy x rays, from 1 keV to 15 keV, and here the properties of various ALS sources, existing and proposed, are benchmarked against the performance of the Advanced Photon Source (APS) , National Synchrotron Light Source (NSLS), and Stanford Synchrotron Radiation Center (SSRL). Although the core program of the ALS will always be in the lower energy region, the complementarity of higher energy techniques and the potential to have a large capacity in this spectral range are powerful arguments for the full exploitation of the capability of the ALS in the intermediate-energy x-ray region.

The flux and brightness are widely used to characterize the quality of a light source and are presented here for the ALS in comparison to other DOE light sources. In the case of microfocus experiments, in general the figure of merit is brightness. For experiments in which neither good angular collimation nor a small focus size are required, flux is the figure of merit. Several classes of experiment, however, have a figure of merit that is somewhere between flux and brightness, and to evaluate the quality of the source, the flux lying within the position·angle or phase-space acceptance of the experiment has to be evaluated. For example, vertical brightness is required in experiments that involve grazing-incidence reflection or diffraction. The demand for brightness is due to the small apparent sample size at small angles of incidence and the required high degree of angular collimation. Another example, in which the figure of merit is closely related to the horizontal brightness, is diffraction from protein crystals where crystal sizes are often a few hundred microns and typical angular collimation is a few milliradians. Care therefore has to be exercised in directly using flux and brightness to compare the characteristics of light sources.

In this note the ALS performance is benchmarked against existing light sources and against an upgraded machine at SSRL. Finally the performance of the ALS with incremental improvements is compared to the APS.

2. Existing Sources

In this section, the performance of the ALS at its standard operating energy of 1.9 GeV is benchmarked against the existing APS, NSLS, and SSRL machines. The graphics indicate for the most part the types of radiation source, so comments are given here only about specific devices and where clarification is needed. The accelerator parameters are given in Table 1 and the radiation-source parameters in Table 2. Note that the accelerator parameters are not fixed in time for any machine, and incremental improvements are constantly being made to increase brightness, for example by a reduction of the vertical emittance. In Figures 1 and 2, the flux and brightness of ALS bend-magnet and wiggler sources are compared to those of the APS bend-magnet, undulator A, and wiggler sources. Figures 3 and 4 show the flux and brightness comparison for selected NSLS sources—a bend magnet, in-vacuum undulator (IVUN), a permanent-magnet wiggler, and a super-conducting wiggler. Figures 5 and 6 show the same comparison for SSRL radiation sources—a bend magnet and 15-, 26-, 30- and 54-pole wigglers. In summary, it can be concluded that in terms of flux, the APS wiggler is the highest output device, with the ALS wiggler being competitive with all the others examined to at least 15 keV. The APS undulators offer extraordinary brightness at high energy, with an advantage over the ALS wiggler of around 300 at 10 keV. The ALS and NSLS wigglers have a similar performance and have more than an order of magnitude advantage over the brightest SSRL wiggler at 10 keV. A surprising result is that an ALS bend magnet has a higher brightness than the SSRL 54-pole wiggler up to 9.5 keV and higher than the 15-pole wiggler up to 14 keV.

Table 1. Accelerator parameters.

Source	E (GeV)	I (mA)	ε_h (m·rad)	ε_v (m·rad)	β_h (ID, m)	β_v (ID, m)	D_x (ID)	β_h (bend, m)	β_v (bend, m)	D_x (bend)	$\delta E/E$
ALS	1.9	400	6×10^{-9}	6×10^{-11}	11.2	4.2	0	0.85	1.46	0.094	8×10^{-4}
APS	7.0	100	5.7×10^{-9}	1.3×10^{-10}	14.2	10.1	0	1.8	18.4	0.085	1×10^{-3}
NSLS	2.58	500	9.4×10^{-8}	1×10^{-10}	1.1	0.41	0.15	1.6	10.5	0.34	8×10^{-4}
SSRL	3.0	100	1.3×10^{-7}	1.3×10^{-9}	16.5	1.9	1.05	2.8	24	0.56	7×10^{-4}
SPEAR3	3.0	200	1.8×10^{-8}	1.8×10^{-10}	14.5	7.0	0	1.0	7.0	0.1	9×10^{-4}

Table 2. Radiation Sources.

Source	Bend Field (T)	Undulator	Wiggler	Wiggler	Wiggler	Wiggler
ALS	1.27 &	λ_0=23mm	λ_0=160 mm			
	5.0	N=40	N=37			
			B_0=2.1 T			
APS	0.6	λ_0=33mm	λ_0=85 mm			
		N=70	N=56			
			B_0=1.0 T			
NSLS	1.22	λ_0=11mm	λ_0=120 mm	λ_0=174 mm		
		N=31	N=27	N=5		
			B_0=1.0 T	B_0=5 T		
SSRL	0.77		λ_0=260 mm	λ_0=175 mm	λ_0=129 mm	λ_0=70 mm
			N=15	N=26	N=30	N=54
			B_0=1.9 T	B_0=2.0 T	B_0=1.5 T	B_0=1.0 T
SPEAR3	1.19	λ_0=33mm	λ_0=260 mm	λ_0=175 mm	λ_0=129 mm	λ_0=70 mm
		N=70	N=15	N=26	N=30	N=54
			B_0=1.9 T	B_0=2.0 T	B_0=1.5 T	B_0=1.0 T

λ_0 is the undulator period, N is the number of poles, and B_0 is the peak field.

3. Comparison to the Spear3 Upgrade of SSRL

The comparison of the ALS to an upgraded SSRL with the SPEAR3 lattice is shown in Figures 7 and 8 for flux and brightness, respectively. In terms of flux, the wiggler performances are similar, and the SPEAR3 bend magnet now has a significantly better performance than the ALS for most of the energy range with an advantage of 4 at 10 keV. In terms of brightness, the ALS wiggler and SPEAR3 54-pole wiggler have similar performance over the whole energy range, and the bend magnets become equivalent at 12.5 keV, with the ALS having better performance at lower energy.

Storage rings and radiation sources can be incrementally improved over time, offering significant performance advantages. Figure 9 and 10 show the flux and brightness of the ALS and the SPEAR3 machine with additional radiation sources. These are by no means a complete set, and clearly with advancing undulator and wiggler technology, as shown by the in-vacuum undulator pioneered at NSLS, substantial improvements can be made.

A 23-mm-period, small-gap undulator has been studied at the ALS to cover the important 1-keV to 4 keV energy range. The performance of this device in flux and brightness is similar to that of the APS undulator A proposed for SPEAR3, although the ALS device would have to use the first through fifth harmonics, whereas the higher energy of SPEAR allows a longer period and requires only the first and third harmonics. The ALS device will tune down to around 300 eV. The use of small gaps also allows the development of more-optimum wigglers, and we have shown here a 50-mm-period device with a 5-mm gap and 40 poles. This device would be operated with two sets of additional quadrupoles to decrease the vertical and horizontal beta values to 0.5 m and 3 m, respectively. This, together with the reduction in length and peak oscillation amplitude, gives an increase in brightness of around a factor of eight at 10 keV.

A project was started in 1993 to investigate the possibility of replacing three of the 36 bend magnets in the ALS lattice with high-field magnets. This study matured into a construction project to build a prototype magnet, and after three years of research and development, the LBNL superconducting-magnet group recently produced a full-scale prototype that has routinely demonstrated a peak field of 6.5 T and a field at the source points of 5 T. This is now a mature technology; moreover, it requires only relatively minor changes to the machine and would have minimal impact on the emittance. Each bend magnet will give light into two ports, and each of these can be split into two beamlines. Three magnets therefore give us the potential to have 12 superconducting bend-magnet beamlines. As shown in Figures 9 and 10, these devices will have excellent performance to above 20 keV.

4. Comparison of Future ALS Sources to the APS

Finally, it is useful to benchmark the subset of possible future devices that we can add to the ALS to those available now at the APS. This comparison is shown in Figures 11 and 12. The 23-mm-period ALS undulator fills in the energy range below that covered by APS undulator A; the small-gap wiggler is competitive with the APS wiggler in terms of brightness; and the superconducting bend magnet offers very similar performance to an APS bend to above 20 keV. For those experiments requiring extremely high brightness in the x-ray range, for example phase-contrast microscopy and coherent scattering, the APS undulators offer outstanding performance. However, for a significant subset of experiments, the brightness of ALS devices may well be sufficient. The prospect of superconducting bend magnets seems to offer an outstanding opportunity in that it will give us a significant number of excellent high-energy x-ray sources for a low cost to complement the already excellent performance of our soft x-ray and VUV sources.

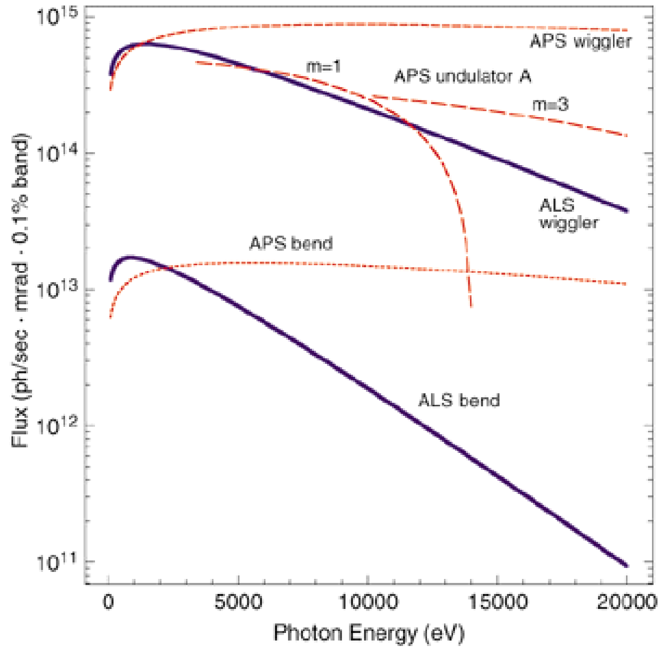

Figure 1. Flux of ALS and APS sources.

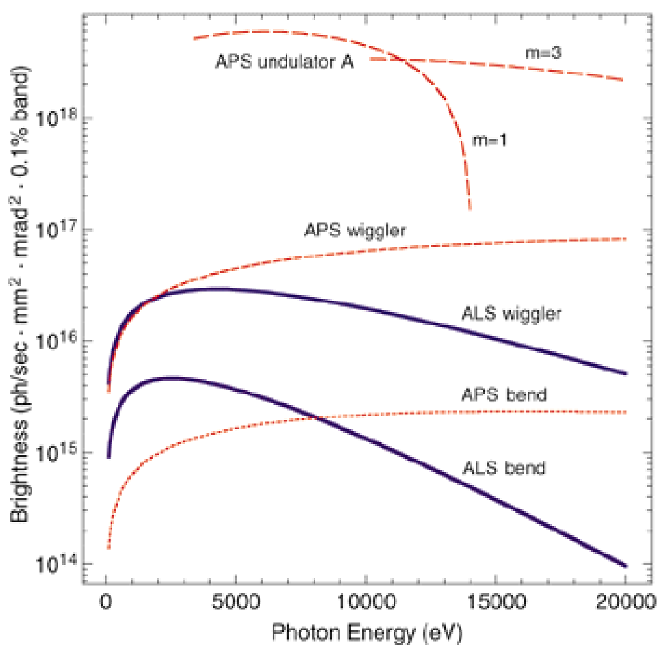

Figure 2. Brightness of ALS and APS sources.

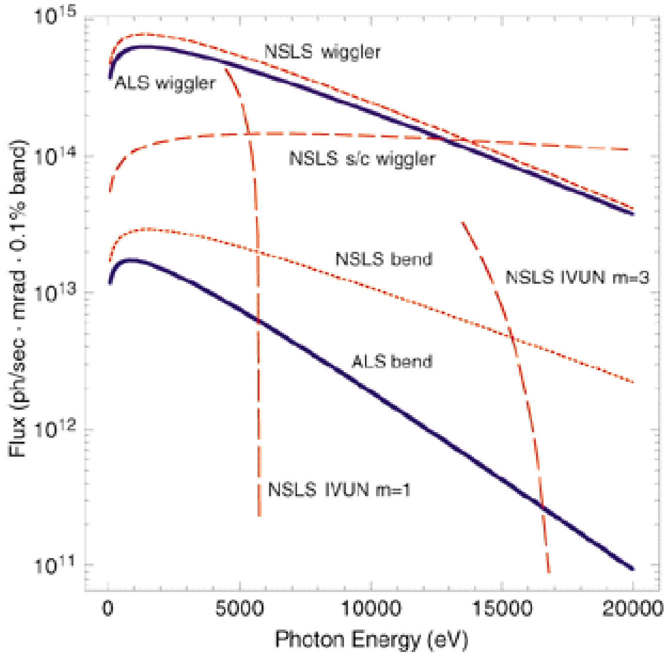

Figure 3. Flux of ALS and NSLS sources.

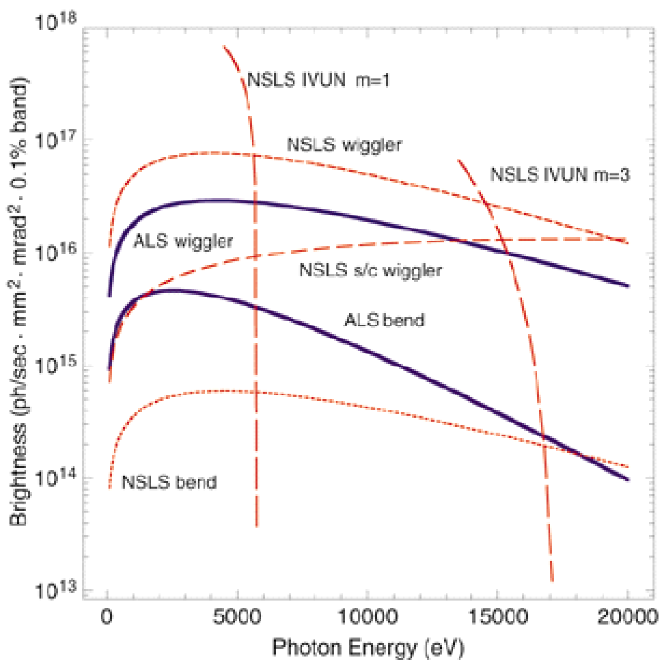

Figure 4. Brightness of ALS and NSLS sources.

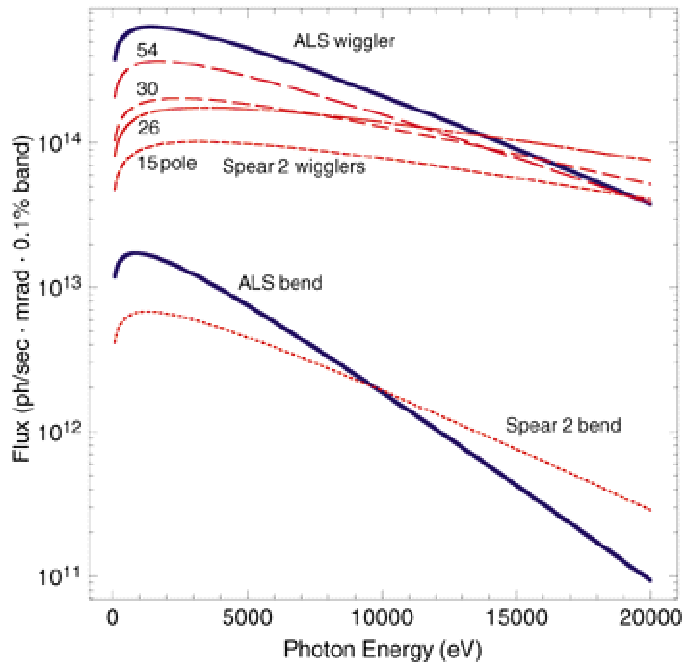

Figure 5. Flux of ALS and SSRL sources.

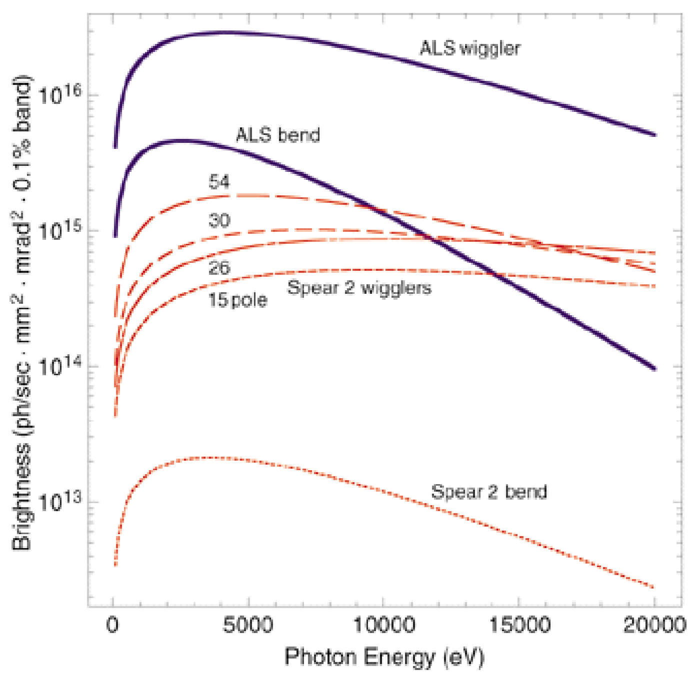

Figure 6. Brightness of ALS and SSRL sources.

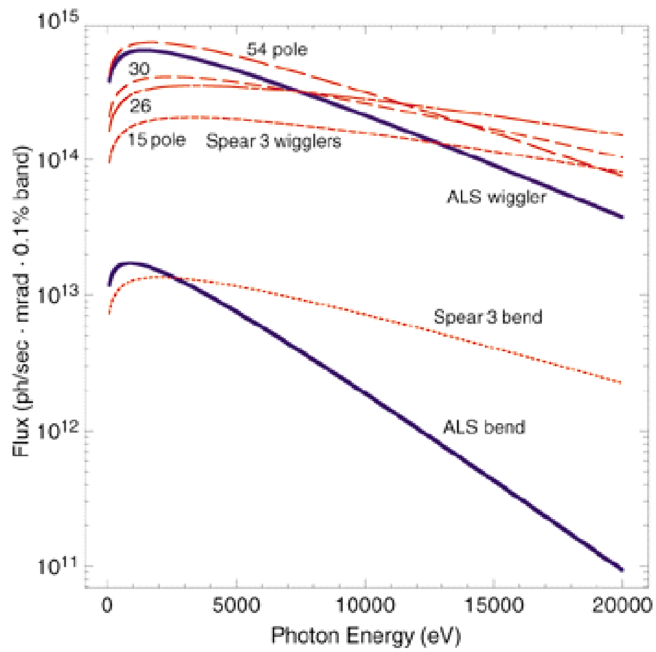

Figure 7. Flux of ALS and SPEAR3 sources.

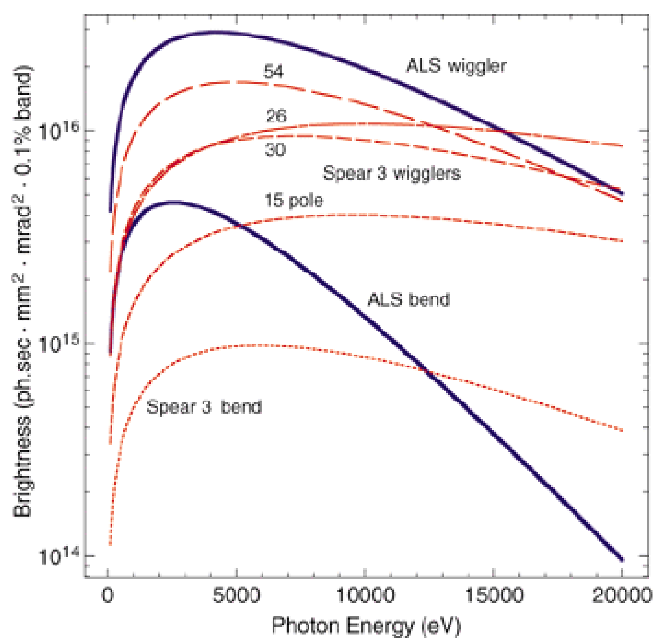

Figure 8. Brightness of ALS and SPEAR3 sources.

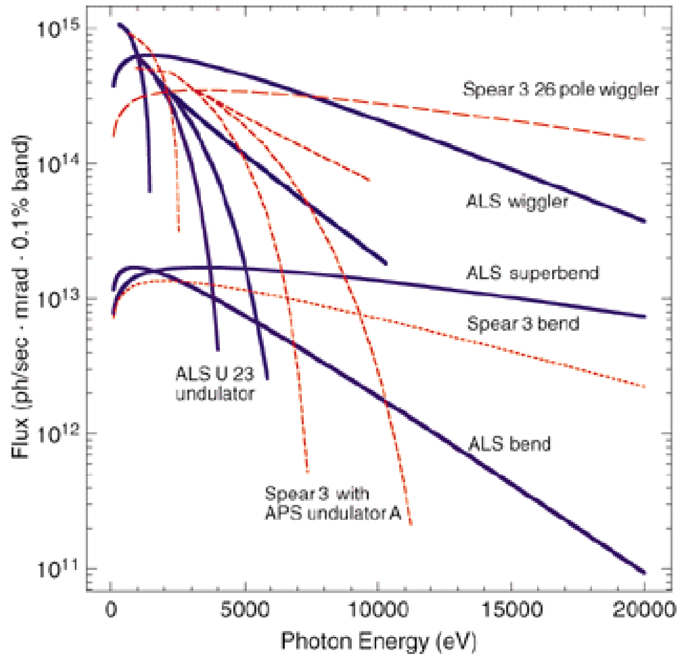

Figure 9. Flux of ALS and SPEAR3 with additional sources.

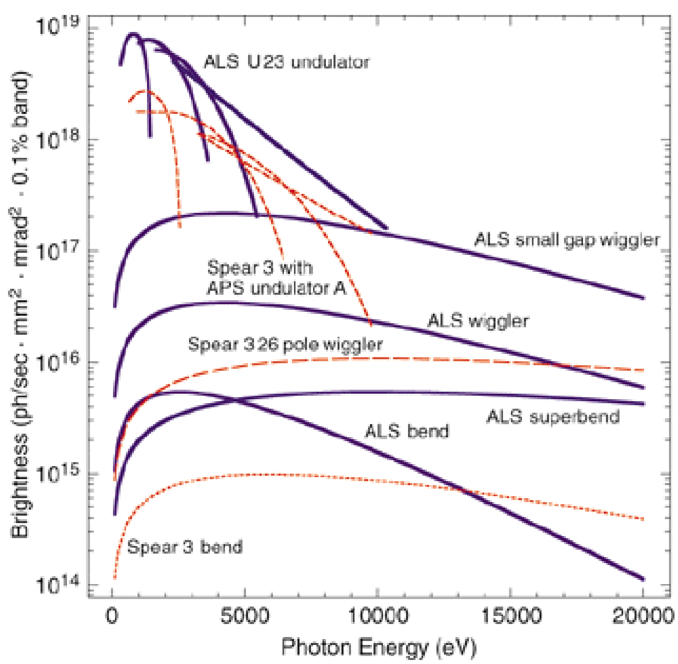

Figure 10. Brightness of ALS and SPEAR3 with additional sources.

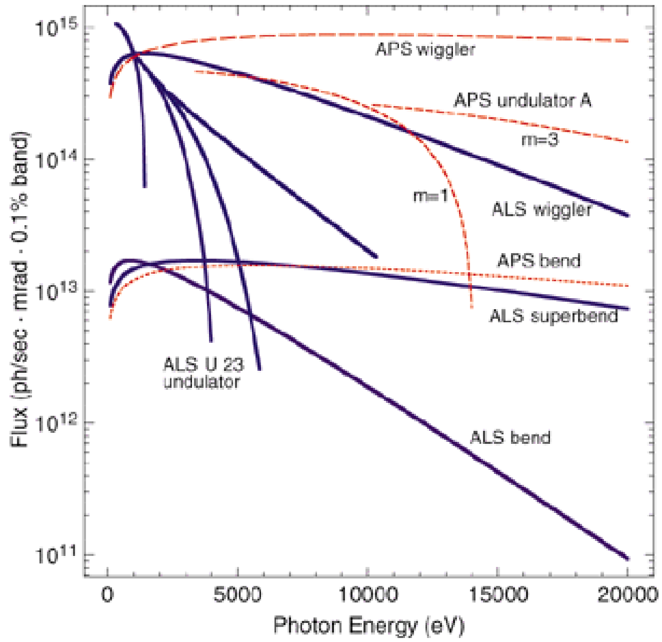

Figure 11. Flux of the ALS with superbends, a small gap undulator and a small gap wiggler and of the APS.

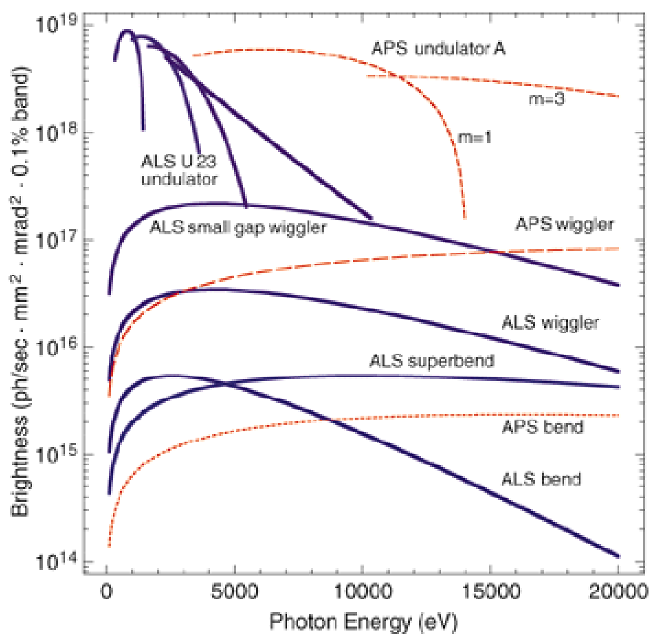

Figure 12. Brightness of the ALS with superbends, a small gap undulator and a small gap wiggler and of the APS.